UCRL 5124

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Radiation Laboratory

THE UNDERGROUND NUCLEAR DETONATION OF SEPTEMBER 19, 1957 RAINIER OPERATION PLUMBBOB

LIVERMORE SITE

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UCRL-5124

UNIVERSITY OF CALIFORNIA
Radiation Laboratory, Livermore Site
Livermore, California

Contract No. W-7405-eng-48

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Gerald W. Johnson, Gene T. Pelsor, Roger G. Preston
and Charles E. Violet

February 4, 1958

Printed for the U. S. Atomic Energy Commission

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ABSTRACT

A nuclear device with an energy release of 1.7 kilotons was fired in a tunnel under a mountain at the Nevada Test Site on September 19, 1957. The objective of the test was to develop a weapons testing technique which would eliminate fallout; be independent of weather; and have no offsite effects such as noise, flash, and shock which do cause some operational difficulties. The principal questions of the general feasibility were concerned with the required depth of overburden required for containment of the radioactivity, the magnitude of the induced ground motions and their associated effects on local and offsite structures, and the possibility of ground water contamination. All of these questions were answered by the test.

Practically all of the radioactivity as well as the heat (about one-half of the device energy release) was contained in a region with a radius of about 60 feet, which is believed to be the approximate radius of the cavity produced by the explosion before it collapsed. The seismic effects though readily measureable were negligible. The fission products appear to have been trapped in highly insoluble fused silica so that the likelihood of ground water contamination is believed to be zero. The success of the experiment added impetus to the Plowshare Project of the Livermore Laboratory -- a project devoted to the study of non-military applications of nuclear detonations. Because of the effectiveness of containment and the negligible seismic effects, it was clear that detonations, even of much larger magnitudes, could be safely fired in many locations. Post-shot drilling revealed that about 500,000 tons of tuff was crushed to sand and at least 200,000 tons of broken tuff was produced by caving. The crushed region was impervious to drilling water while the caved region was very permeable to both water and gas. Measurements of the temperature distribution three months after the detonation revealed temperatures up to 90°C still existed in the central region. A rough integration of the total thermal energy at temperatures above ambient gives one-half the total energy release. It was estimated that initially about 700 tons of the medium was heated to the fusing range (1200°C - 1500°C). Because of the presence of large amounts of water in the rock (15 - 20% by weight) and the collapse of the initial cavity, the temperature probably quickly dropped to the vicinity of 100°C.

ACKNOWLEDGMENT

This report is a summary of the preliminary results of the nuclear detonation fired deep underground at the Nevada Test Site on September 19, 1957. The results contained here were obtained from measurements made by groups from the following organizations:

1. U.S. Geological Survey
2. U.S. Coast and Geodetic Survey
3. Armour Research Foundation
4. Sandia Corporation
5. Engineer Research and Development Laboratories
6. Stanford Research Institute
7. Broadview Research Corporation
8. Edgerton, Germeshausen and Grier, Inc.
9. University of California Radiation Laboratory at Livermore

The over-all responsibility for the design and execution of the experiment belonged to the University of California Radiation Laboratory at Livermore, California. The technical success of the test is the result of the cooperative efforts of the several scientific teams.

THE UNDERGROUND NUCLEAR DETONATION OF SEPTEMBER 19, 1957 RAINIER

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I. INTRODUCTION

Early in 1956, it was proposed by D. T. Griggs and E. Teller* that serious consideration should be given to the possibility and the economic feasibility of testing nuclear weapons underground. The success of the method would lead to many practical operating benefits, such as the total absence of fallout, the elimination of air-blast and noise damage, or nuisance, to off-site communities, no interruption or interference with airline traffic during passage of the radioactive cloud, and the removal of the need to be concerned about the possible effect of the bright flash on the vision of motorists. The net effect would be the removal of the dependence on weather for testing of weapons in Nevada, which in turn would avoid extensive delays and reduce costs of the operation because of the elimination of the need for off-site fallout monitoring and weather forecasting.

Before these benefits are to be obtained, however, many vital questions required answering, with the costs being weighed against the benefits. First of all are the technical questions of measurements of the weapon's performance. It was clear from the outset that those experiments requiring close collimation, and massive shielding, could be more readily accomplished underground than on towers. The major experimental concern centered on the problems associated with obtaining suitable radiochemical samples. In air, yield is determined by radiochemical methods and by rate of fireball growth. The latter is a hydrodynamic method employing high speed cameras to record the growth of the fireball. For underground

*D. Griggs and E. Teller, Deep Underground Test Shots, UCRL-4659, Feb. 21, 1956.

shots, it was anticipated that there would be difficulty in recovering radiochemical samples. Also, because of possible fractionation of the appropriate fission products, significant results might not be derived. Consideration was also given to the methods of measuring hydrodynamic yield underground by shock time-of-arrival measurements at various points in the medium.

Besides the diagnostic problems just described there were those having to do with costs, depth of burial, effects of surrounding media, ground water contamination, and seismic effects.

II. PRELIMINARY STUDIES

The study of the general concept and feasibility of the underground testing technique was undertaken by the Test Division, UCRL, at Livermore during the Spring of 1956. For the first test it was desired to fire a device of known proved yield and reaction history, and in the interest of keeping costs to a minimum, to use one with a low yield. A device was selected whose performance was known so that monitoring of the rise of the nuclear reaction would assure proper functioning. The energy release was 1.7 kt.

Preliminary costs for a test of this yield were developed based on the assumptions of horizontal tunnels under mountains, vertical shafts, and vertical drill holes. It soon became clear for reasons of convenience of installation of equipment and for a yield of the magnitude mentioned that a horizontal tunnel would be the choice. The cost of vertical shafts was found to be three or four times as much as for horizontal tunnels, and while drilling costs are about the same as for horizontal tunnels, drilled holes are much less convenient to instrument and, in case of difficulty, greatly complicate trouble-shooting.

Preliminary calculations and design of the experiment were carried out by B. Sussholz.* In this work he concluded that the depth of burial, D, for complete containment of the radioactive material would be

$$D = 300\ W^{1/3}$$

where D is in feet and the yield, W, is in kilotons. For W = 1.7 kt, D = 360 ft. This differs from the Griggs and Teller result where it was estimated that for Yucca Flat about 600 ft would be required to prevent cratering and 1,000 ft to assure containment for 1 kt. Because of

*Now at Ramo Wooldridge Corp., Los Angeles, Calif.

uncertainties in relating nuclear explosives with HE, the tunnel was designed to provide at least twice the depth of burial as calculated by Sussholz. Sussholz designed a self-sealing tunnel in which the shock from the explosion would collapse the tunnel before the shock could progress down the tunnel itself, thus, preventing the ejection of radioactive material. His estimates of the seismic effects led to the conclusion that it was safe to fire the proposed shot by several orders of magnitude.

The field coordination of this test was assigned to C. E. Violet of UCRL and plans to include it in Operation Plumbbob were developed. G. T. Pelsor further refined the theoretical work initiated by Sussholz and designed an improved and simplified version of the tunnel as it was finally constructed (Fig. 1).

The U. S. Geological Survey undertook investigations to determine the geological structures in the region near the point of detonation, to study such aspects of the containment problem as could be accomplished with high explosives, to determine seismic effects of the HE for scaling to the proposed nuclear shot, and to measure typical physical properties of the medium of interest in the theory. Two high explosive shots, one of 10 tons and one of 50 tons (60% nitroglycerin gelatin), were detonated at the test site. The 10-ton shot was at a depth of 92 ft and the 50-ton shot at 165 ft. Scaling these depths up to the Rainier yield (1.7 kt) would give equivalent depths for that yield of:

$$D = 92 \times (1700/10)^{1/3} = 507 \text{ ft} \qquad (10 \text{ tons})$$

$$D = 165 \times (1700/50)^{1/3} = 534 \text{ ft} \qquad (50 \text{ tons})$$

The conclusions from these USGS studies were that while no crater would be expected from the Rainier event, it was anticipated that the rock would be fractured to the surface and possibly considerable spalling would occur. In addition, it was predicted that large blocks of rock would be dislodged from the top of the mesa. It was thought that small quantities of radioactive gases, explosion products, and solid or liquid products would also escape. Based on the USGS study, additional stemming was recommended for the tunnel. Seismic waves generated by the Rainier explosion were expected to be below damage levels at a distance of about 10 miles. (Damage zone was regarded as the region in which the acceleration exceeded 1 g.) With respect to earthquakes it was stated that a coincidental natural

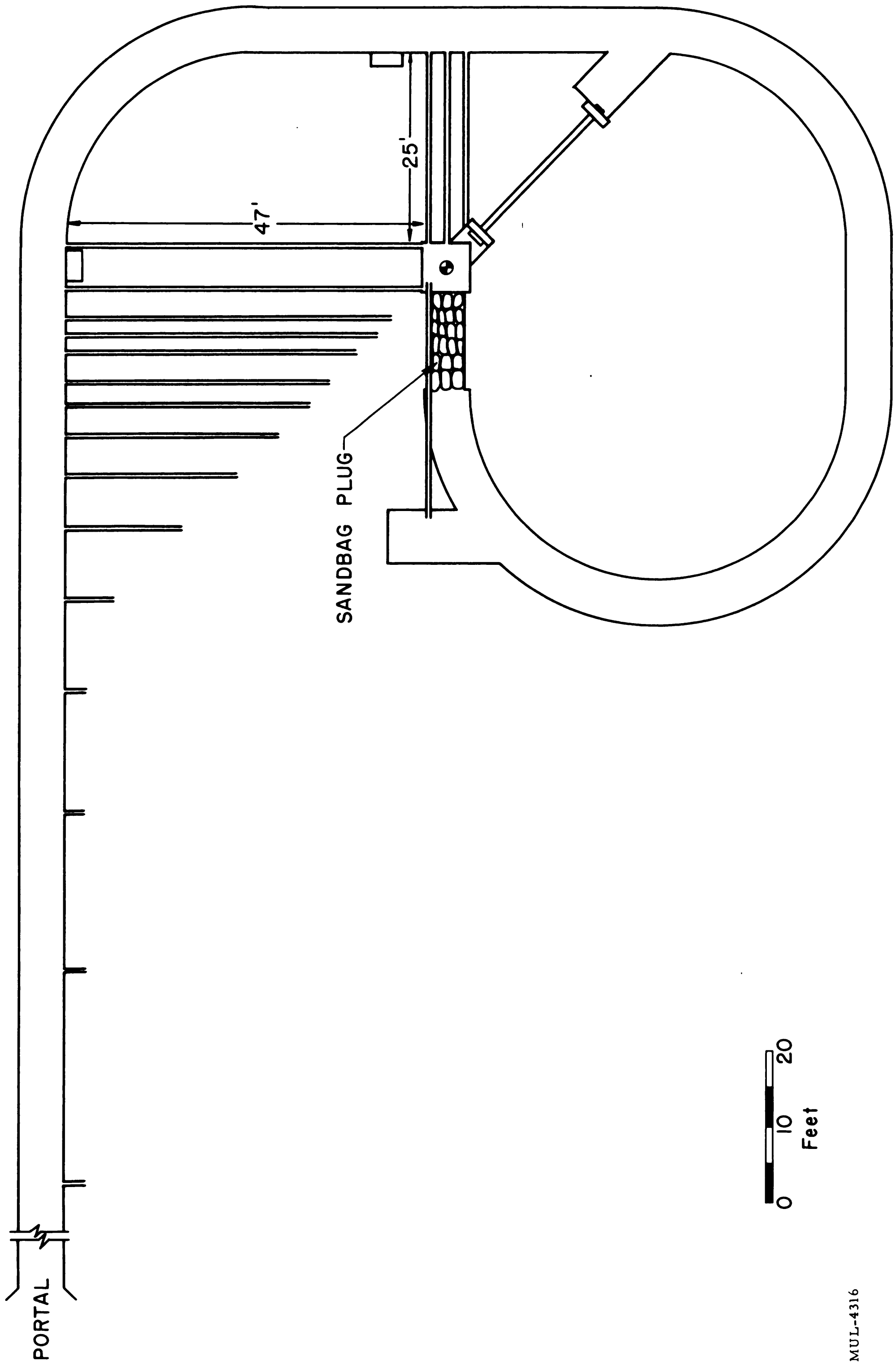

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Fig. 1 — Pre-shot tunnel configuration in region of detonation.

shock was unlikely, and it was considered extremely unlikely that the test would trigger a natural earthquake.

At the request of Mr. L. Strauss, Chairman of the AEC, an advisory panel was established for the Albuquerque Operations Office to examine the question of the probability of triggering an earthquake, to study the frequency of natural earthquakes in the area to provide an estimate of the probability of a coincidental earthquake, and to consider the ground water contamination problem.

The advisory panel was composed of the following specialists:

Seismology and Geophysics

Roland Beers — Rensselaer Polytechnic Institute, Troy, New York
Perry Byerly — University of California, Berkeley
David Griggs — University of California at Los Angeles

Ground Water Contamination

George B. Maxes — Illinois Geological Survey, Urbana, Illinois
Sheppard T. Powell — Baltimore, Maryland

At a general review of the problem with the Atomic Energy Commission on April 17, 1957, the advisory panel stated that the proposed shot would not generate seismic signals any larger than those produced by the largest airbursts already fired in previous test series; it would not be felt in Las Vegas; and it would not trigger a natural earthquake in any area. Earthquakes themselves do not do this. If any fault in the area were about to go and if shocks could release it, then earlier tests or more likely the great Nevada earthquake of December 16, 1954, would have done so.

It was also concluded that the possibility of ground water contamination was very remote.

The Commission at this meeting gave the final go-ahead on Rainier, subject only to reconsideration if any new information should develop which would qualify seriously the conclusions of the advisory panel.

III. SCIENTIFIC PROGRAM

The technical objectives of the test were:

1. To test the containment calculations.

2. To measure physical characteristics of the medium pertinent to the theory of the explosion and to record any changes in them after the explosion.

3. To obtain acceleration, displacement, and pressure measurements in the medium surrounding the point of detonation.

4. To measure shock velocity in the medium in the supersonic region in an attempt to calculate yield.

5. To recover radiochemical samples and to determine their usefulness from a yield measurement standpoint.

6. To measure and evaluate seismic signals and effects at distances extending from the point of detonation out to all distances where the signals could be detected.

7. To measure the reaction history as a check on the performance of the device.

In the interest of making the detonation of use to the geophysical community the date, time, location, and approximate yield of the device were released prior to the firing of the device.

Subsequent to the establishment of the experiment for test technique purposes, interest developed in studying the feasibility of applying underground nuclear detonations to oil field exploitation, mining and power. Thus, in the interpretation of the results, and in the emphasis in this report, these additional interests were considered.

Topographic and Geologic Features of Site

Figure 2 illustrates schematically the general topography and some geologic characteristics of the Rainier site. The rock formation in which the shot took place has been named Oak Springs tuff. Similar material deposited from volcanic activity during the Tertiary age is found throughout the Nevada Test Site. The Rainier tunnel was driven horizontally into the sloping side of a mesa in the northwest section of Yucca Flat. The shot chamber, as indicated in Fig. 1, was located vertically below the mesa surface at a depth of 900 feet. Surface zero was about 150 ft from the edge of the mesa.

The rock underlying the formation at the site is a dense crystalline limestone. Over this basement rock eight generally distinguishable beds of tuff (deposited volcanic ash) have been laid down. These tuffs vary considerably in degree of cementation between the particles of minerals. Unit 7, Tos_7 in Fig. 2, is variably, but very weakly, cemented. At some depths cementation of the rock is so weak that the material approaches the

DESCRIPTION OF BEDDINGS

Tos_8	-	Welded tuff; rhyolite to quartz latite
Tos_7	-	Bedded tuff; mostly loosely cemented and "sandy"; light gray to grayish brown
Tos_6	-	Welded tuff; light gray to brownish gray
Tos_5	-	Bedded tuff; well cemented; light yellow green
Tos_4	-	Bedded tuff; well cemented; light gray to buff, some pink
Tos_3	-	Bedded tuff; well cemented; red at top and base, pink to buff interbeds
Tos_2	-	Bedded tuff; mostly light gray to buff
Tos_1	-	Bedded tuff; purplish to pinkish red
Dd	-	Limestone; hard, dense, crystalline; medium to dark gray

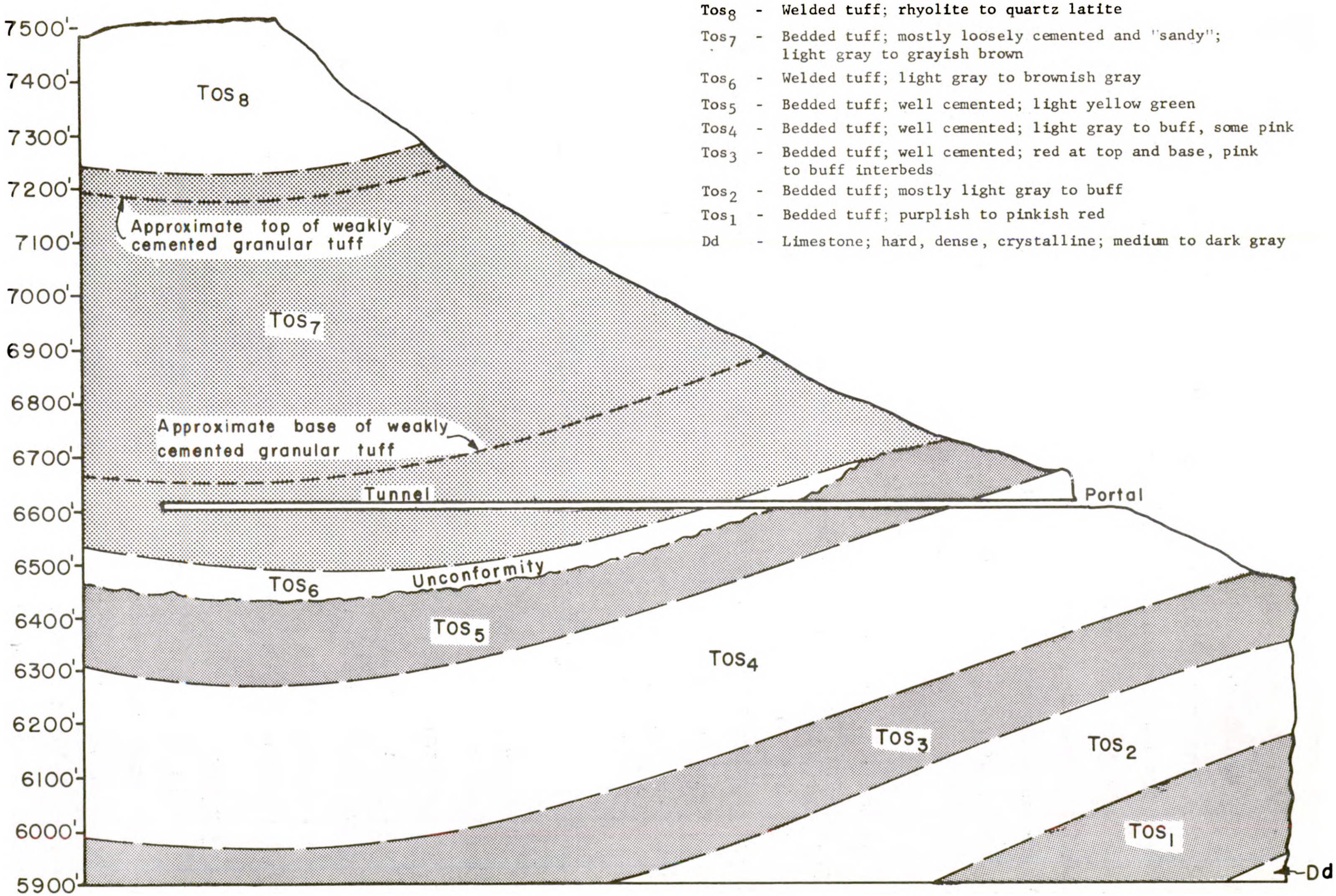

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Fig. 2 — Profile of tunnel site with geologic characteristics.

consistency of loose sand. At tunnel depth cementation was sufficient so as not to require timbering of the tunnel. The limestone basement in the immediate area of the Rainier site, somewhat variable in elevation, lies about 1900 ft below the mesa surface.

Except at the rim of the mesa, where the tuff has been welded, the slope conforms to the maximum angle of repose for the detritus, about 30 degrees from the horizontal. At the rim, the rock stands in vertical blocks 50 to 100 ft high separated by jointing action of the past.

The underlying beds of tuff in the Rainier site are gently tilted, moderately jointed and slightly faulted. Only one small fault was crossed by the Rainier tunnel. While evidence indicates the tuff was deposited, at least partly, in shallow fresh-water lakes, only one bed of conglomerate was crossed by the Rainier tunnel.

Directly over the shot chamber, the first 250 ft from the top is a welded tuff with low porosity (15 to 25%) and virtually no fluid permeability. The welded tuff is partially to fully saturated with water. The interval 250 ft to 850 ft is mostly loosely cemented granular tuff with a porosity of 25 - 35%, and is apparently fully saturated. At greater depths and in the area in which the tunnel was constructed the tuffs were well cemented.

Physical Properties of the Medium Prior to Detonation

The physical properties listed in the following table are intended to represent our best estimates of the average properties of the medium within 100 ft of the center of detonation. The samples were all collected in the vicinity of the point of detonation prior to the shot. The magnitudes often represent averages of measurements made by various groups. The tabulated data are based on measurements made by George V. Keller of the USGS, Earl Parker of the University of California, and E. C. Robertson of the USGS.

Density:

Bulk density in situ	1.9 - 2.0 g/cm^3
Bulk density dry	1.70 ± 0.1 g/cm^3
% Water by weight	15% - 20%
% Voids connected	25% - 35%
Density corrected for connected voids	2.29 ± 0.05 g/cm^3

Most of the water is released from the rock by heating to 110°C.

At this temperature 80% of the water is released, by heating to 600°C another 18% is released, and about 2% more by heating to 1000°C.

Bulk Modulus:

2.1×10^{12} dynes/cm^2

Compressive Strength:

5,000 - 10,000 psi

Thermal Conductivity (at 29.0° ± 0.3°C):

Dehydrated	$K = 1.70 \times 10^{-3}$ cal/cm sec deg.
Saturated	$K = 2.60 \times 10^{-3}$ cal/cm sec deg.

Sound Velocity:

Sound velocity in the material around the point of detonation was measured to be 7900 ft/sec.

Chemical Composition (Partially dried):

SiO_2	- 70 ± 3%	K_2O	- 4.5 ± 1%
Al_2O_3	- 12 ± 1.5%	H_2O	- 7.5%
Fe_2O_3	- 1.5 ± 1%	MgO	- 0.5%
Fe O	- 0.05 ± 0.01%	CaO	- 1% ± 0.5
Na_2O	- 1.8 ± 0.2%	CO_2	- 0.2%

Petrography:

The rocks are tuffs consisting primarily of glass with phenocrysts of quartz and orthoclase. There are relatively few crystals of the above minerals in the rocks. A weak X-ray pattern for cristabalite was obtained.

Fusion Tests:

Cones prepared from crushed samples were heated in a furnace. All deformed in the range 1280 - 1300°C. On account of the large glass content no great volume change would be expected on fusing.

IV. RESULTS

Rainier was fired at 09 hr 59 min 59.45 sec on September 19, 1957, Pacific daylight time. The coordinates of the detonation were 37° 11' 44.80" N lat., 116° 12' 11.35" W long. The elevation of the top of the mesa above the point of detonation was 7514 ft and the center of the room was 6615 ft. All elevations are with respect to mean sea level. The bomb was located in the center of a room with dimensions 6' x 6' x 7'. The room was plugged with 13 ft of sandbagging starting from the entrance to the room. The only other barriers were two steel doors designed to support 75 psi at positions 575 ft and 1,225 ft from the point of detonation.

The firing was accomplished from a control point located at a distance of 2.5 miles from the point of detonation. At this location a weak ground wave was felt by a few people and a muffled explosion was heard. The immediate visible effects of the explosion were the slight ripple which spread over the face of the mesa as the pressure wave reached the surface and the breaking loose of some of the rocks comprising the crown of the mesa, which then rolled down the slopes of the mountain.

On making a detailed survey, except for the mentioned loosening and falling of rocks from the crown and some superficial cracking of the surface directly over the point of detonation, no other damage to the mountain was apparent. Detailed radiological surveys of the area revealed that there had been no detectable venting of radioactive materials at any point.

The shot tunnel was entered and the door at 575 ft from the point of detonation was reached four hours after detonation. Except for occasional spalls and a shift of a few inches of one bedding plane at approximately 1100 ft from the point of detonation, the tunnel was intact. In the last 200 ft in approaching this door the CO content of the air began to increase and reached 400 parts per million at the door. The CO presumably was formed by effect of shock-heated air on organic material, such as cable insulation, located in the tunnel. The alpha, beta, and gamma radiation levels were the same as those read prior to the detonation. The background gamma radiation level in the tunnel is 0.04 mr/hour.

For operational reasons it was decided to wait a few days before opening the inner door at 575 feet to survey further the effects of the explosion. This was done on September 24, 1957, and the tunnel penetrated to within 200 ft of the center of detonation.

From about 500 ft toward the zero point there was more damage to the tunnel than was apparent in the first part. Large slabs were displaced from the sides and overhead, filling the tunnel with debris to a depth of about 2 ft. The tunnel appearance was of this same general nature until the point of closure was reached. This occurred at 200 ft from the point of detonation. At this point the wall appeared to have been displaced radially from the point of detonation by about 2 ft and the floor forced upward about an equal distance. The rest of the opening was closed by broken and crushed rock. Typical damage to the tunnel is shown in Fig. 3. The CO concentration in this area was about 500 parts per million. Again, however, the radiation levels at all points did not exceed the background levels. The tunnel design had been completely successful in containing the radioactive products of the detonation.

In view of the uncertainties associated with the distribution of energy around the point of detonation and the possibility of the existence of cavities at high temperature and pressure, it was decided to vent the cavity by drilling from the top of the mesa. The drilling system with built-in safety features was designed for remote operation in the event that the drill penetrated a high pressure region. This turned out to be very time-consuming because of the fact that beneath the hard cap of the mesa (about 250 ft thick) there is a layer 600 ft thick of loosely consolidated material. However, on November 1, the drill broke into a cavity at 385 ft above the point of detonation. The depth of this cavity was found to be 25 ft. Photographs made in the cavity indicated broken tuff and sand had collected in the bottom of a roughly conical cavity. The volume then was estimated to be at least of the order of 15,000 ft^3.

Gas samples were collected from the cavity and solid samples from the bottom of the cavity. The concentrations of the fission products analyzed are expressed in terms of the total fissions in the original device: (1.45×10^{23} fissions produce a yield of 1 kt)

<u>Gas</u>	Kr^{85}	- 5-9 x 10^{14} fissions/ft^3
<u>Solid</u>	Nd^{147}	$\sim 10^9$ fissions/kg (traces)
	Y^{91}	

The radiation level in the cavity as read with an ion chamber gave the normal backgound reading of 0.04 mr/hour. A temperature measurement in the

(a)

(b)

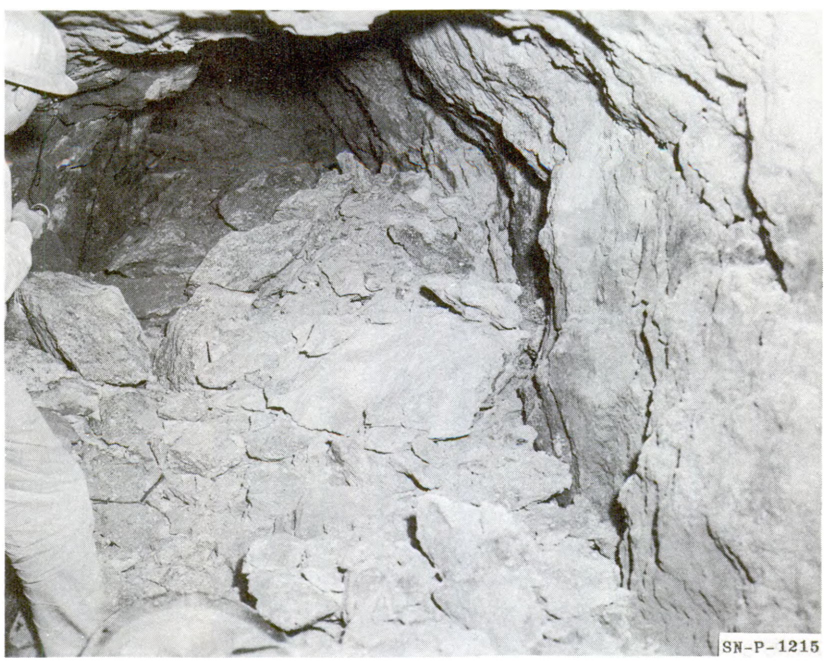

Fig. 3 — Typical post-shot damage to tunnel. (a) Looking toward the point of collapse in the Rainier tunnel at a distance of about 400 ft from ground zero. (b) View of the point of collapse about 200 ft from ground zero.

material at the bottom of the cavity gave 12.2°C, which was the same as measured at the same depth in a nearby hole prior to the shot.

This cavity established the boundary of the upper extension of the activity of the device. The drill hole was pushed down as rapidly as possible and ultimately reached the same elevation as the zero point displaced radially 17 ft. Between the cavity and the maximum depth reached the material was sand and broken tuff, and there was no drilling water return. On preshot coring the material was found to be lightly cemented to within 50 ft of the point of detonation. During this part of the drilling operation 68,000 gallons of water were lost to the medium. At no point in the drilling vertically from the mesa were any high-pressure regions or pockets encountered. Since the level where the device had been detonated was reached without encountering a pressurized zone, it was clear that concern from this hazard could be dismissed.

Now that it was safe to drill from within the tunnel, all drilling operations were shifted to this location. A set of lines of drilling was established from a position 211 ft from zero (Fig. 4). The first hole was aimed to penetrate directly through the point of detonation. The hole was drilled and logged for temperature and radioactivity. The results are shown in the curves of Figs. 5 and 6.

It will be noted that the temperature reaches a peak value of 45°C at a radius of 60 ft, and then decreases to a fairly constant value of 33°C ± 2° from 35ft in to zero. In holes B and C temperatures as high as 90°C have been observed. (At this altitude water boils at about 94°C.) The detailed temperature distibution will not be available for sometime. A rough calculation of the total thermal energy now contained in the heated volume gives one-half of the total energy release of the device. When the total balance is measured the thermal content is expected to comprise a much larger fraction. The radioactive regions were divided into two zones: The first region extended about 75 ft to 60 ft, with gamma radiation levels of 200 to 400 mr/hour and a second narrow region about 53 to 43 ft with a peak level of 800 mr/hour. Throughout these regions the returned core material was mostly sand with occasional short cores a few inches long but crushable by hand. The appearance of the cores in the radioactive region did not differ markedly from those in other regions. However, occasional sintered pieces of rock were found and are being studied radiochemically.

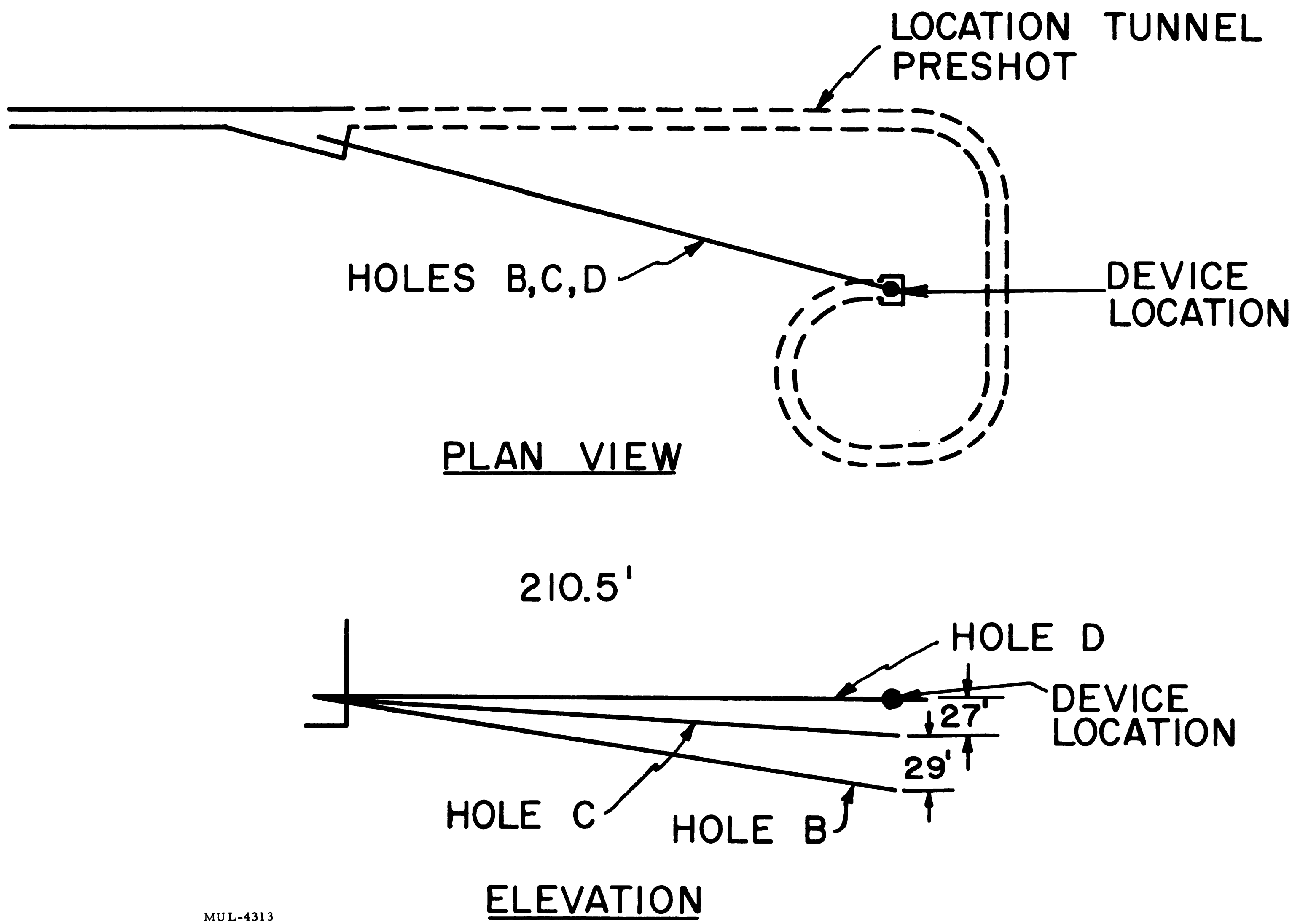

Fig. 4 — Locations of post-shot drill holes.

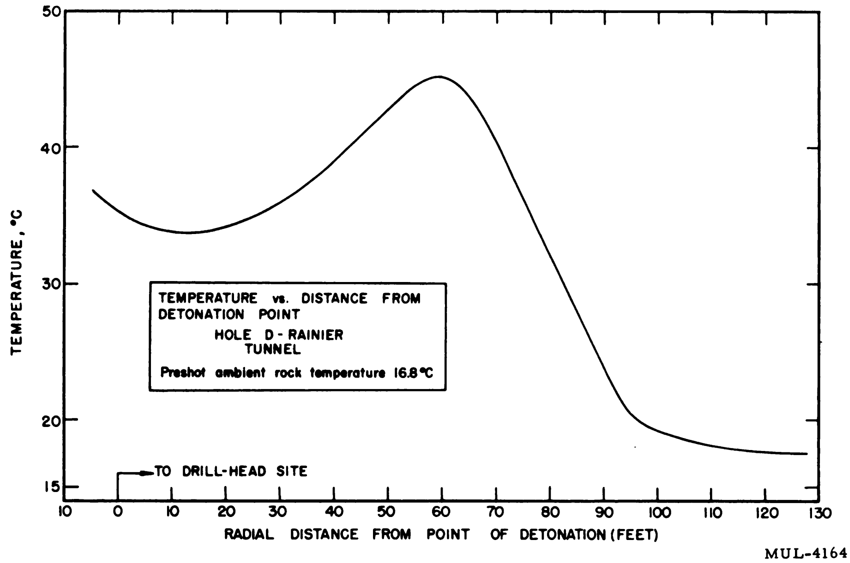

Fig. 5 — Post-shot temperature log of hole D.

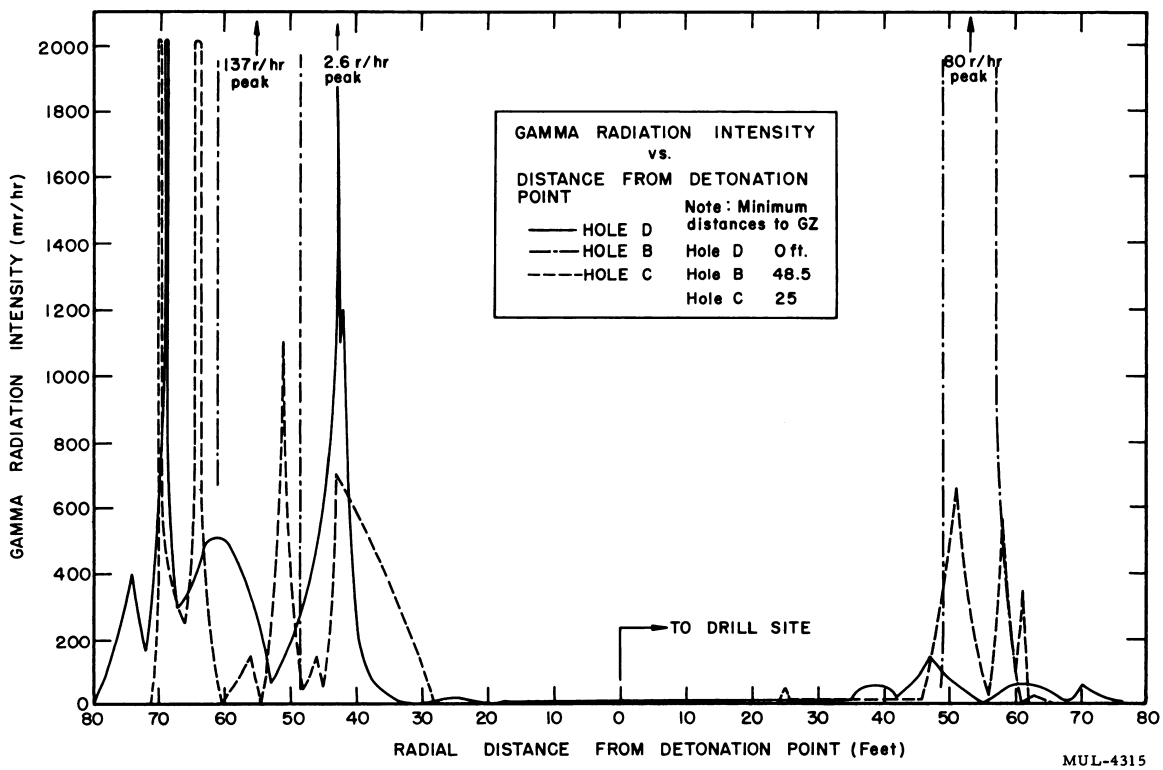

Fig. 6 — Post-shot radiation logs of holes B, C and D.

Beyond a radial distance of 130 ft from the center of detonation the rock as indicated by corings appeared to have the same properties as before the shot. Inside this radius the material was loosely consolidated. However, the circulation of drilling water was complete until the highly radioactive zone was reached at about 55 ft. Inside that region the return flow of water was essentially zero, indicating that the gross permeability was much higher.

Drilling along two other lines was then carried out. One was directed at 50 ft below the point of detonation and the other 20 ft below. (Refer to Figs. 4 and 6.) On these runs highly radioactive cores were recovered. The active samples were found to contain activities corresponding to 3.4×10^{14} fissions/gram. It must be observed that this number is based on a single sampling and may be found to be quite different when the sampling is complete.

Since in the explosion of the device there were 2.5×10^{23} fissions and since it now appears that most of the radioactivity is trapped in the once-fused material the estimated mass of tuff melted is $\frac{2.5 \times 10^{23}}{3.4 \times 10^{14}} = 7 \times 10^{8}$ g and volume $\sim 3.5 \times 10^{8}$ cm^3.

The general appearance of the active material is glassy with bubbles and containing many inclusions of granular tuff of various degrees of fusion. Crude estimates of the temperature reached by the material indicate a range of 1200°C - 1500°C. The bulk density of the samples measures 1.8 g/cc which is not greatly different from the preshot values.

With these numbers and the drilling results it is possible to reconstruct the general geometry of the explosion. The shot region as it is now believed to exist is shown in the sketch Fig. 7. It consists of a central region of radius 55 ft about the point of detonation and extends upward 400 ft to the void. Measurements of Kr^{85} gave the same concentration at the top and bottom showing that the radioactive gas was uniformly mixed in this region. This central region is also permeable to water and steam as evidenced by the facts that water circulation in the drilling was lost throughout the volume and that heat was quite evenly distributed near the bottom. Outside the central permeable region is a shell of crushed but impermeable (to drilling water) tuff out to a radius of 130 ft.

The major radioactive material is contained in a zone about 10 ft in thickness from a radius of 47 - 57 ft. No activity was discovered outside this radius, except the very small amount of Kr^{85} which had reached the cavity at the top of the permeable zone and traces of Nd and Y.

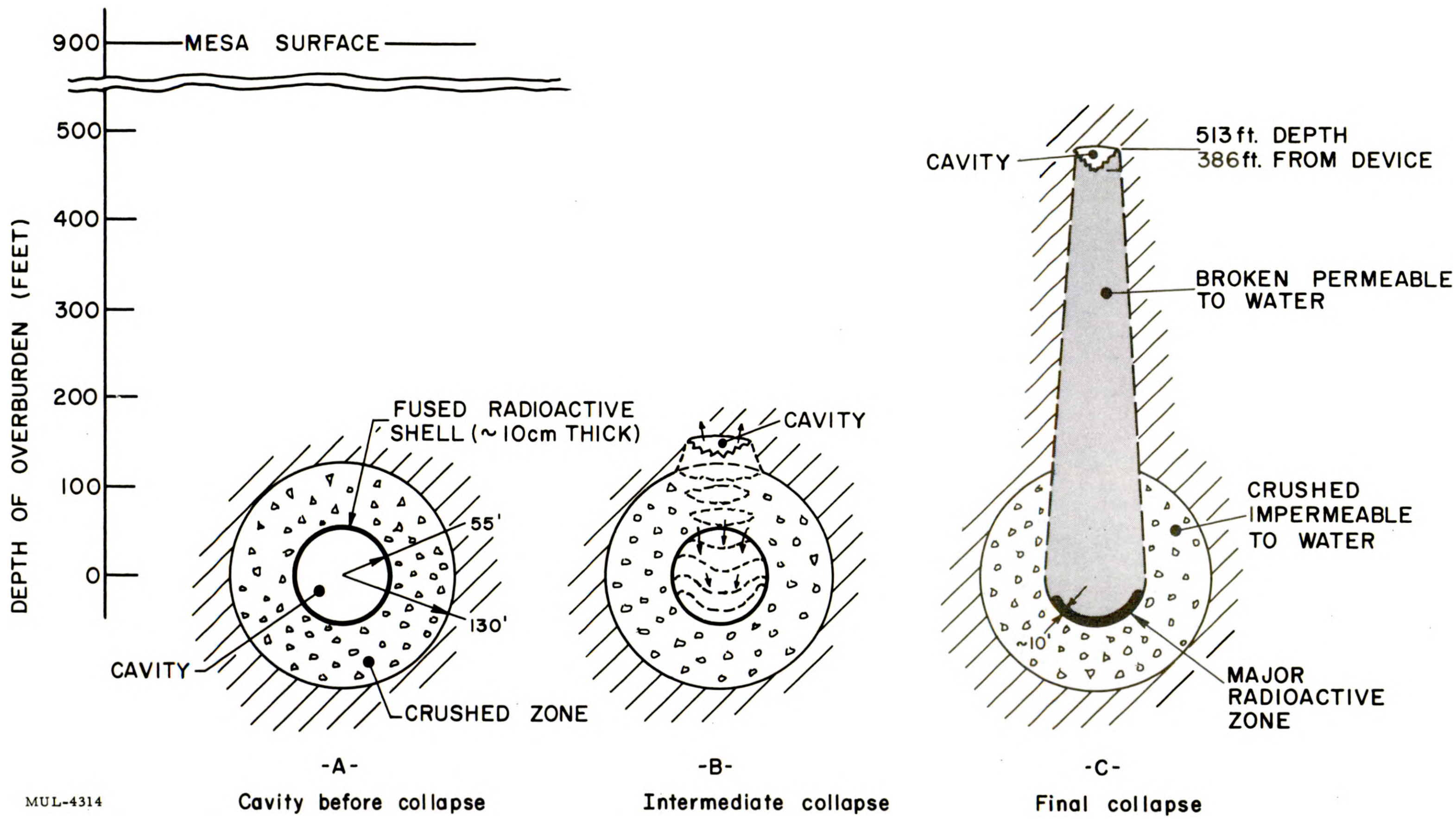

Fig. 7 — Reconstructed picture of strongly affected zones surrounding detonation point.

As stated earlier, about 7×10^8 g of material reached a temperature in the range of 1200°C to 1500°C. Assuming that 400 calories per gram were required to bring the tuff to this temperature, then $7 \times 10^8 \times 400 = 3 \times 10^{11}$ calories were needed. Associated with this mass of tuff was about $0.20 \times 7 \times 10^8 = 1.4 \times 10^8$ g of water. To heat the water would require an additional $1.4 \times 10^8 \times (80 + 540 + 700) = 1.8 \times 10^{11}$ calories, using a specific heat for water of 1 cal/g, heat of vaporization of 540 cal/g, and a specific heat of 0.5 cal/g for steam. The total energy then in this fused material and associated water was $\sim 5 \times 10^{11}$ calories or about 30% of the total energy released.

The general sequence of the events that occurred shortly after detonation may now be constructed. (Refer to Fig. 7.) It appears that a spherical cavity having a radius 55 ft was formed early, the inner surface of which was fused tuff. The thickness, t, of the shell was, then, based on the volume of melted material, $t = \frac{\text{volume}}{4\pi R^2} = \frac{3.5 \times 10^8}{4\pi\,(55 \times 30)^2} = 10$ cm. The shell collapsed probably immediately. Material moved in radially and the roof fell in. The collapse proceeded vertically until a structure was reached of sufficient strength to support the cavity roof. The broken once-melted shell containing most of the radioactive products was subsequently distributed in a layer of broken tuff a few feet thick. It cooled very quickly by mixing with the cooler tuff and by convective cooling from the water vapor. Assuming a mixing of the fused shell with 5 ft of material contained in a shell of an interior radius of 50 ft would give a mean temperature of 100°C as the following rough calculation shows:

$$V = \text{Volume of shell} = 4/3\pi\,(55^3 - 50^3)\,(30)^3 = 4.6 \times 10^9 \text{ cm}^3$$

$$M = \rho V = 9 \times 10^9 \text{ g}$$

Since the material is 20% water, of this mass 2×10^9 g is water and the remainder is solid. To heat this mass of material from 16°C to 100°C requires $(7 \times 10^9 \times 0.3 \times 84) + (2 \times 10^9 \times 84) = 3 \times 10^{11}$ cal. This leaves 2×10^{11} calories to evaporate water and the quantity of water vaporized would be $\frac{2 \times 10^{11}}{540} = 4 \times 10^8$ g, which would leave 1.6×10^9 g of water still in the liquid state. Thus the high temperatures (1200°C - 1500°C) persisted for only a short time and soon fell to the vicinity of 100°C.

A rough estimate of the shock pressure as a function of radial distance from the detonation is shown in Fig. 8. The pressure on the wall of the room

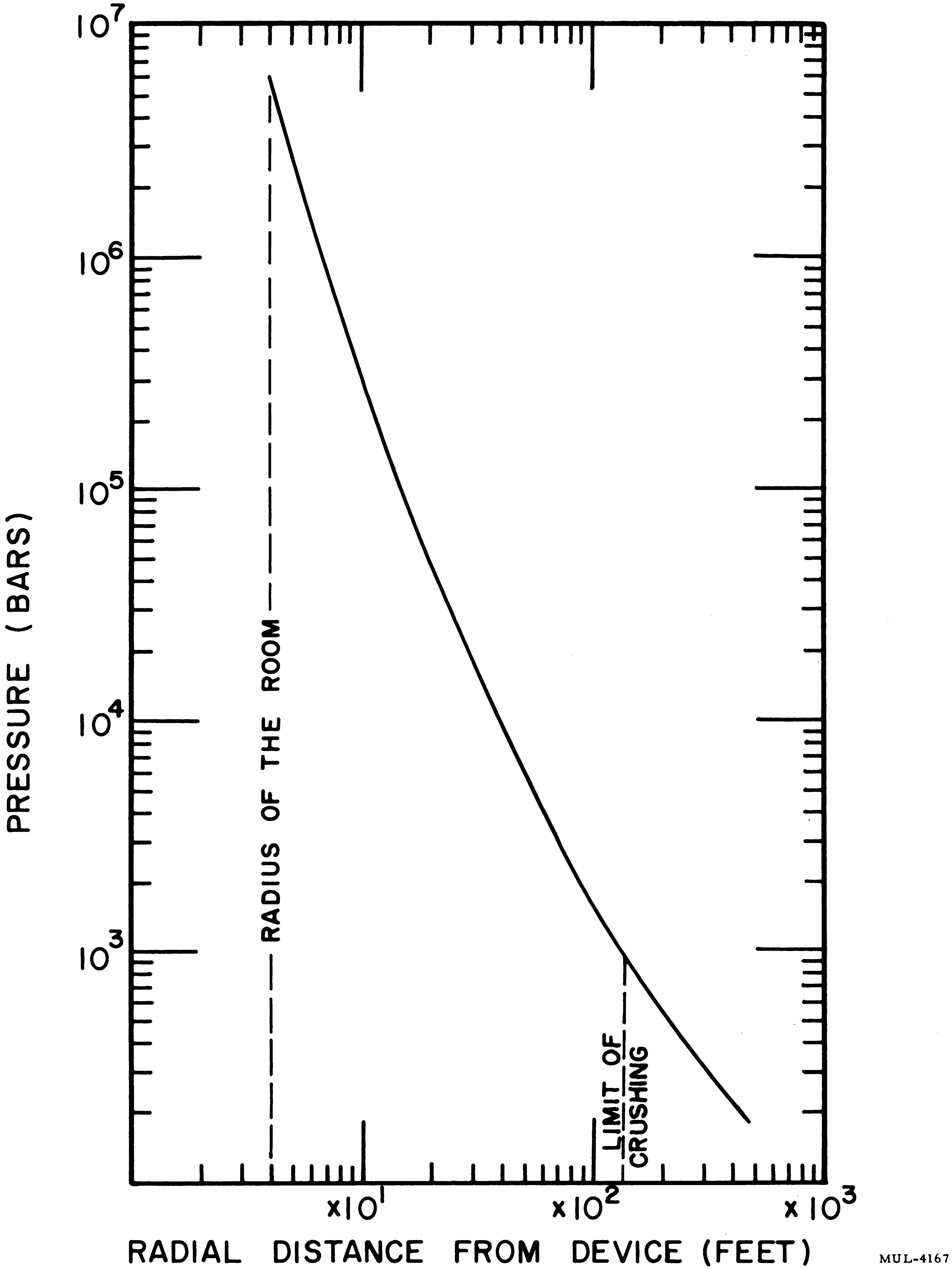

Fig. 8 — Estimate from theory of shock pressure vs radial distance.

as the shock entered the rock was about six megabars as calculated from the energy density at that time. At 130 ft, the pressure had dropped to the crushing strength of the rock under dynamic loading--estimated as 1 or 2 kilobars. The shock pressure required to melt the rock is probably greater than 10^5 bars, so the fused material which is now found 55 ft from the center was originally contained in a sphere of radius 10 to 15 ft about the point of detonation. Using a radius of 15 ft the calculated mass of material melted by the shock would be 10^9 g, which is consistent with the value derived from the radiochemical data (7×10^8 g).

Displacements and Accelerations

At Rainier, acceleration measurements were made in three principal areas: along the surface of the mesa extending to a range of 2500 ft; in vertical holes drilled from the mesa toward the shot chamber; and at several stations a few feet below the tunnel floor. A preliminary analysis of the data indicates that the maximum radial acceleration in both the vertical and horizontal directions from the detonation falls off inversely with the fourth power of distance out to 700 ft. There is some indication that the radial acceleration in the vertical direction is weaker than that in the horizontal direction; i. e., the former, at the same range, is 60 per cent of the latter. Possible explanations for the differences are (a) the material above the chamber was weaker and more compressible so that the shock was more rapidly attenuated, and (b) energy may have been channeled between more or less horizontal beds of rock having somewhat different propagation properties.

At ground zero on the mesa the observed peak acceleration was 5.8 g. Below the surface the acceleration decreased to about 1 g at 200-ft depth and then increased toward ground zero in accordance with the fourth power law. The records of the surface gages and some of the deeper gages indicate that a block of rock separated and moved upward, reached a peak displacement at the mesa zero surface of about one foot, and then fell back. The vertical displacement decreased with distance radially from surface zero becoming negligible at 500 to 600 ft. The data indicate that the rock parted at least 100 ft, possibly as deep as 300 ft below the surface.

Permanent net displacements of stations in the Rainier tunnel were determined from the results of pre-shot and post-shot surveys. The closest recoverable station, located in the floor of the tunnel at 203 ft from the detonation point, was displaced 3 ft horizontally and 2-1/4 ft upward. At the 700-ft

range the net horizontal displacement was 1 ft. Within 1100 ft all horizontal displacements were to the south and east; and the maximum horizontal component for each surveyed point was approximately in the direction of a radial line from the detonation point. Beyond the previously mentioned bedding plane at 1100 ft radial distance, net horizontal displacements were outward but to the north and east. At the portal the displacement was about 0.8 ft.

Seismic Effects

Ground motions from Rainier were measured by the USC & GS and USGS. At ranges from 1200 ft to 3-1/2 miles from the shot, the USC & GS employed strong-motion seismographs developed for studying damaging earthquakes. Beyond 3-1/2 miles the USGS employed velocity meters. The Coast Survey found the peak acceleration to scale according to the relation $A = 0.06\ W^{0.75}\ R^{-2}$, where A is in g's, W in kt and R in miles. The USGS data were not in disagreement with the closer-in measurements of the USC & GS.

At the observers' position, 2-1/2 miles from the shot, the peak acceleration was about 0.02 g. Very few people detected any ground motion. As far as seismic effects are concerned, Byerly has concluded that yields at least two orders of magnitude higher than Rainier could be detonated underground without appreciable effects on the test site facilities.

The USC & GS also studied Rainier records from permanently located Wood-Anderson seismographs. These instruments are calibrated and the interpretation of seismograms from them in terms of magnitudes for earthquakes is fairly well understood. Records were available from seven of these stations located 110 to 350 miles from the test detonation. Based upon the Coast Survey's analysis, the seismic signals from the Rainier shot corresponded to an earthquake of magnitude 4.6 on the Gutenberg-Richter scale. Such a disturbance originating from movement in the earth's crust would be perceptible as far as 60 miles from the epicenter; yet, the Rainier shot was perceptible to only a few individuals standing 2-1/2 miles from the shot. The Coast Survey has compared records from Rainier and those from the Port Hueneme earthquake of 18 March 1957. The comparison was made with records from stations where the seismic signals were of comparative strength and where, for the earthquake, the works of man were affected. The records from the two situations were found to have many similar characteristics. On

this basis, the Coast Survey would have concluded that the Rainier detonation produced surface effects which were similar to those of an earthquake, and which, potentially, were damaging. However, in the case of Rainier, peak accelerations greater than 1g were confined to a radius of less than 1100 ft. Reasons for the discrepancy are not understood at present.

It is clear that the source conditions in the two cases are vastly different. Energy from an earthquake is released from slippages along faults usually at great depths and often many miles long. In California, these slippages occur most frequently at 10 miles or more depth. Energy from the Rainier detonation was released at a very shallow depth into a highly localized region.

The Gutenberg-Richter magnitude calculated from long-range seismic observations of Rainier and the deduction therefrom concerning the range of perceptibility for an earthquake of that magnitude are matters of considerable interest. It can be concluded that the Gutenberg-Richter magnitude as devised for describing natural earthquakes drastically overestimates the intensity and range of any damaging effects resulting from a buried nuclear detonation.

V. CONCLUSIONS

1. The radioactive products of nuclear detonations can be completely contained in underground explosions. The radioactivity from Rainier was completely contained within a radius of 60 ft. For the medium used (tuff) this radius, R, should be proportional to $W^{1/3}$, so that $R = 50\ W^{1/3}$ ft, W = yield in kt.

2. The depth of burial for complete containment is certainly less than $670\ W^{1/3}$ and it is now estimated that $D = 450\ W^{1/3}$ ft would be acceptable.

3. Seismic effects were quite small and from a public annoyance standpoint were zero. From the seismic measurements it was concluded that shots with yields higher than Rainier by at least two orders of magnitude could be safely fired at the Nevada Test Site.

4. Experiments requiring good collimation and massive shields can best be accomplished underground.

5. Results are not conclusive but it appears that practically all the fission products are trapped in highly insoluble fused rock so that there will be no ground water contamination problem.

6. In tuff Rainier produced at least 200,000 tons of permeable broken rocks and in addition about 500, 000 tons of crushed but relatively impermeable material. The tonnage of the two kinds of material should scale in direct proportion to energy release for a moderate range of yield. These large masses of broken material suggest applications in mining to break up ore bodies for removal or leaching, and to oil field exploitation. It must be recognized of course that for other media different kinds of effects and magnitudes would be expected.

7. In rocks containing large amounts of water the temperature is likely to be reduced to 100°C quite rapidly, and the heat will be distributed over large volumes. This wide distribution of heat coupled with the breaking up of the medium might be applicable to increasing the production of oil in certain situations.

8. The Gutenberg-Richter magnitude, devised for describing natural earthquakes, overestimates the intensity and range of any damaging effects resulting from a buried nuclear detonation.